SELECTIVE EXPERIMENTS IN PHYSICS

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EXP. No. .....

ELECTRIC FIELDS

OBJECT: To examine certain electric fields; in particular to map the equipotential lines of an electric field and hence determine the electric lines of force.

METHOD: A conducting plate with silvered metallic terminals, shown as shaded areas in Fig. 1, is fastened beneath the field-mapping board. An electric field is produced by connecting these terminals at X and Y to a source of potential. Points of equal potential in this field are discovered by a movable exploring probe connected to a sensitive null-point detector. The series of points C′, all of the same potential as C, define an equipotential line. By moving the contact to D another equipotential line, points D′ may be similarly plotted across the field. In this way the entire field is explored. The U-shaped probe is used to transfer the discovered equipotential points to the student's record sheet which is attached to the top of the field-mapping board.

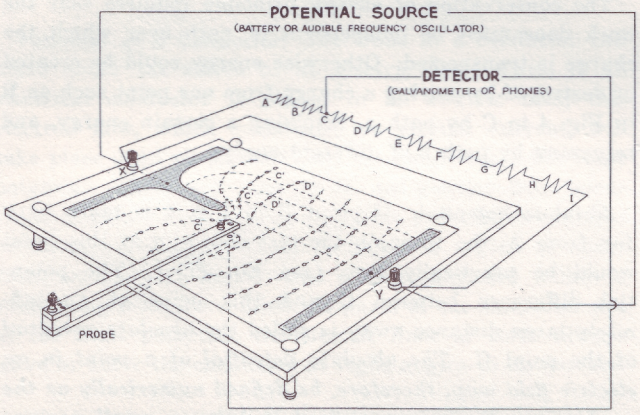

Fig. 1. Diagrammatic Representation of Electric Field Apparatus.

THEORY: Coulomb's Law: The first quantitative investigation of the law of force between electrically charged bodies was carried out by C. A. Coulomb in 1784-1785. His measurements showed that the force of attraction for unlike charges or of repulsion for like charges followed an inverse square law of distance of separation. It was later shown that for a given distance of separation r the force is proportional to the product of the individual charges, Q and Q′, and is a function of the nature of the medium surrounding the charges. Expressed in symbols, Coulomb's law is

$$F \propto QQ'/Kr^2$$

where the factor K, called the dielectric constant, is introduced to take care of the nature of the medium. The factor K is arbitrarily assigned a value of 1 for empty space. Coulomb's law is restricted to point charges, that is, the charged body must have dimensions which are small compared to the separation distance.

Systems of Units: Several systems of units, each with its particular advantages, are in use. The *electrostatic system* will be emphasized in this experiment. In the electrostatic system forces are expressed in dynes, distances in centimeters, and the unit of charge, called the statcoulomb, is chosen of such magnitude that the proportionality constant in Coulomb's law is equal to unity. Thus Coulomb's law may be expressed by

$$F = QQ'/Kr^2 \qquad (1)$$

Unit Quantity of Electricity or Charge: When all quantities in Equation (1) are unity the definition of the electrostatic unit (esu) of charge or statcoulomb is indicated — *The statcoulomb is a charge of such magnitude that it is repelled by a force of 1 dyne when placed 1 cm from an equal charge in vacuum.* The charge of one electron is a natural basic unit of quantity of electricity. Its charge is 4.80×10^{-10} statcoulomb. Thus 1 statcoulomb represents a charge of 2.09×10^9 electrons or approximately two billion electrons. For practical use, however, the statcoulomb is exceedingly small and a charge known as the coulomb or ampere-second is used. The coulomb is approximately equal to three billion statcoulombs.

Dielectric Constant: The factor K in Coulomb's law, called the *dielectric constant* of the medium, is assigned a value of 1 for vacuum. When the medium separating the charges is not empty space, the force between the charged bodies is altered because charges are induced in the molecules of the medium. Air at one atmosphere pressure has a dielectric constant of 1.00059. Thus as a practical matter, Eq. (1) using $K = 1$ is acceptable to one part in two thousand for Coulomb's law experiments in air.

The common dielectrics have "constants" K from 1 to 10 in value. The dielectric constant of glass ranges from 5 to 10. mica from 3 to 6 and oil from 2 to 2.5. The specific value of the "constant" for a given medium may vary with a change in temperature, pressure, frequency of current, etc. It is noted also that K is not a pure number but has dimensions dependent on the system of units used.

Electric Fields: An electric field, commonly called field of force, is a region in which forces act on electric charges if present. If a force F acts on a charge q at a point in the field, the field strength E, by definition the force per unit charge, is

$$E = F/q \qquad (2)$$

that is, *the magnitude of electric field strength is the force per unit charge.* Force is a vector quantity having direction as well as magnitude. *The direction of an electric field at any point is the direction of the force on a positive test charge placed at the point in the field.*

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Lines of Force: Faraday introduced the concept of lines of force to visualize the strength and direction of an electric field. A *line of force* is the path which a free test charge would follow in traversing the electric field. The path is everywhere tangent to the field direction at each point. As an illustration, consider the isolated positive charge Q placed at A in Fig. 2. A small positive test charge q at any point in the field experiences a radial force of repulsion from A. The lines of force are drawn with arrows to point this direction. When Q is a negative charge, that is an excess of electrons, these lines would be directed towards A to indicate an attraction of the positive test charge q.

The magnitude of the force per unit charge may also be graphically shown by the artifice of lines of force. By convention, the number of lines of force drawn through a unit area placed normal to the field at the point considered, is made numerically equal to the field strength. For example, if the field strength at a point is 5 dynes per statcoulomb, one visualizes 5 lines of force per square centimeter at that position in the field.

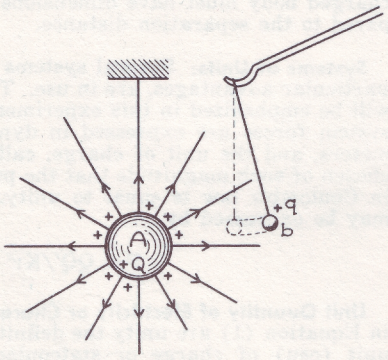


Fig. 2. Electric field around an isolated positive charge.

The diagram of Fig. 3 shows a plane section near a pair of equal charges of opposite sign. Each charge exerts a force on a unit test charge placed in the field. The resultant force is the vector sum of these forces. Thus, at the point b, f_1 is the repulsion force on the unit test charge due to the positive charge on A, and f_2 is the force of attraction to the negative charge on B. The resultant R is tangent to the line of force at the point b.

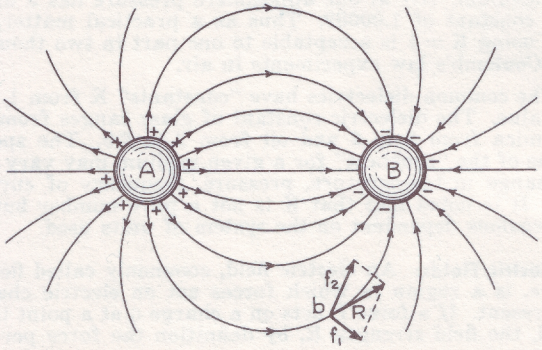


Fig. 3. Electric field near two equal charges of opposite sign.

It is evident that a uniform field is represented by a set of parallel lines of force. A converging set of lines of force indicates a field of increasing strength; while a field of decreasing strength would be represented by a diverging set of these lines.

Potential Difference: Two points in an electric field have a difference of potential if work is required to carry a charge from the one point to the other. This work is independent of the path between the two points. Consider the simple electric field illustrated in Fig. 4. Since the charge $+Q$ produces an electric field, a test charge $+q$ at any point in the field will be acted upon by a force. Hence it will be necessary to do work to move the test charge between any such points as B and C at different distances from the charge Q. *The potential difference between two points in an electric field is defined as the ratio of the work done in moving a small positive charge between the points considered to the charge moved.* In symbols

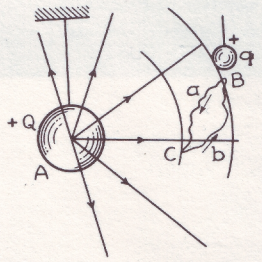


Fig. 4. Potential difference between points in an electric field.

$$V = W/q \qquad (3)$$

where V is the potential difference, W is the work done and q is the charge moved. In the electrostatic system V is expressed in statvolts when W is in ergs and q in statcoulombs. One statvolt is approximately equal to 300 volts. If the work W is measured in joules and the charge q in coulombs then the potential difference V is measured in volts.

The conservation of energy principle requires that the work done must be independent of path over which the charge is transported. Otherwise energy could be created or destroyed by moving a charge from one point such as B in Fig. 4 to C by path a, involving a certain energy, and returning by path b of different energy.

Absolute Potential: If point B in Fig. 4 is taken very far from A, the force on the test charge q at this point would be practically zero (see Eq. (1).). The potential difference between C and this point at an infinitely large distance away is called the *absolute potential* of the point C. *The absolute potential of a point in an electric field may, therefore, be defined numerically as the work per unit charge required to bring a small positive charge from a point outside the field to the point considered.*

Since both work and charge are scalar quantities, it follows that potential is a scalar quantity. The potential near an isolated positive charge is positive, while that near an isolated negative charge is negative. (What is the physical significance of negative work?)

Equipotential Surfaces: It is possible to find a large number of points in an electric field, all of which have the same potential. If a line or a surface is so drawn that it includes all such points, the line or surface is known as an *equipotential line or surface.* The line C'C' in Fig. 1 is an equipotential line. A test charge may be moved along an equipotential line or over an equipotential surface without doing any work.

Lines of Force Perpendicular to Equipotential Surfaces: Since no work is done in moving a charge over an equipotential surface it follows that there can be no component of the electric field along an equipotential surface. Thus the electric field or lines of force must be everywhere perpendicular to the equipotential surface. Equipotential lines or surfaces in an electric field are more readily located experimentally than lines of force, but if either is known the other may be constructed as shown in Fig. 5. The two sets of lines must everywhere be normal to one another.

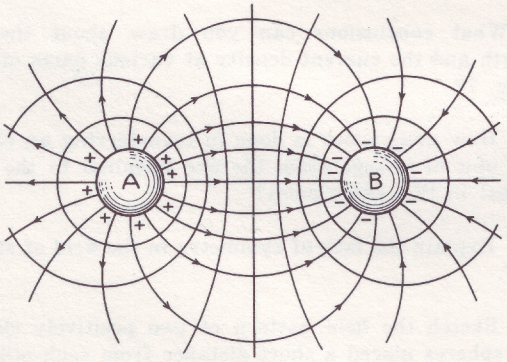


Fig. 5. Lines of force and equipotential lines near two charges of equal magnitude and opposite sign.

The field of Fig. 1 is a reproduction of an actual test made in designing a part for a high voltage generator. The solid lines are the equipotential lines and the dash lines are the lines of force for a field existing between a pin and a plane.

Potential of a Conductor: Electrons in a conductor can move under the action of an electric field. Thus, if an electrical conductor is placed in an electric field, this electron flow, which constitutes an electric current, will take place until all points in the conductor reach the same potential. There will then be no net electric field inside the conductor whether solid or hollow provided it contains no insulated charge. Thus, to screen a region of space from an electric field it need only be enclosed within a conducting container. Since all parts of the conductor are at the same potential, the electric lines of force always leave or enter the conductor at right angles to its surface.

Lines of Flow: When charged bodies of different potentials are located in a medium in which some flow of charge can occur, the field of force will cause these charges to be transported from one body to the other. To maintain the difference of potential the bodies must then be connected to a source of electromotive force. The flow lines of the charge follow the paths of the lines of force, that is, they are also at all points perpendicular to the equipotential surfaces.

APPARATUS: Field mapping board and U-shaped probe, Fig. 1. Field plates with conductive and corresponding templates. The eight similar resistors connected in series (A to I Fig. 1) are mounted on this board. Source of potential ((a) battery or (b) audio oscillator). Null-point detector ((a) sensitive galvanometer or (b) headphones).

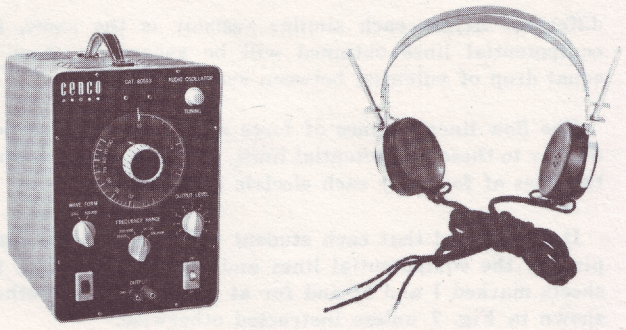


Fig. 6. Audio Frequency Oscillator and Head Phones.

The sensitive galvanometer (Weston 440) is a good detector for locating the equipotential points when a 2 to 6 volt battery is used as a source. The probe is moved to positions of zero readings on the galvanometer. When the source is an audio oscillator, Fig. 6, the headphones are substituted for the galvanometer. With this arrangement equipotential contacts of the probe make the oscillator inaudible.

The student or instructor may prepare his own design, see Fig. 7. The conducting terminals are painted on the colloidal graphite coated plates using Conducting Silver Paste. (Cat. #79589-6) A conducting area in the field is produced by painting in the desired form. If a nonconducting area is desired, a section of the coating is removed from the plate sheet. Thus an unlimited number of different fields may be investigated.

PROCEDURE: Carefully place the selected pattern of Fig. 7 on the underside of the field mapping board and secure it to the conducting terminals X and Y, using the two thumb screws provided. Connect the potential source to X and Y as shown in Fig. 1. When the voltage is applied to the terminals, charges flow between them across the field plate following the lines of force of the electric field established. This same potential difference will be equally divided between the end terminals of the series of similar resistors.

Fasten a sheet of paper, preferably graph paper, on the upper side of the field-mapping board. Trace the corresponding template design on the graph paper using the template.

Connect the null-point detector, galvanometer or phone, to the U-shaped probe and to a fixed point on the resistors, for example C, Fig. 1. The U-shaped probe is now moved over the sheet to find a zero reading position. This point C′ must be at the same potential as C. The circular hole in the top arm of the probe is directly above the contact point which touches the coated plate, thus, the location of the equipotential point may be directly transferred to the graph paper. Move the probe to another null-point position. Continue in order to find a series of these points across the paper. Connect these equipotential points with a smooth curve to show the equipotential line of the same potential as C.

Move the terminal to a new position, for example D, and find its corresponding equipotential line. Repeat for all terminals of the series of resistors. Since the potential

difference across each similar resistor is the same, the equipotential lines obtained will be spaced to show an equal drop of potential between successive lines.

The flow lines or lines of force are everywhere perpendicular to these equipotential lines. Draw in, by dash lines, the lines of force for each electric field studied.

It is expected that each student will complete the mapping of the equipotential lines and the lines of force for sheets marked I and II and for at least one of the others shown in Fig. 7 unless instructed otherwise.

QUESTIONS:

1. Why are the equipotential lines near conductor surfaces parallel to the surface and why perpendicular to the insulator surface mapped?

2. Is it possible for two different equipotential lines or two lines of force to cross? Explain.

3. Explain, with the aid of a diagram, why lines of force must be at right angles to equipotential lines.

4. Under what conditions will the field between the plates of a parallel plate capacitor be uniform?

5. How does the electric field strength vary with distance from an isolated charged particle?

6. Sketch the equipotential lines for an isolated negatively charged particle, spacing the lines to show equal difference of potential between lines.

7. Compare the sketch in answer to Question 6 with the mapped field of the "Parallel Plate Capacitor." Account for the difference.

8. Show that the electric field strength is equal to the potential gradient.

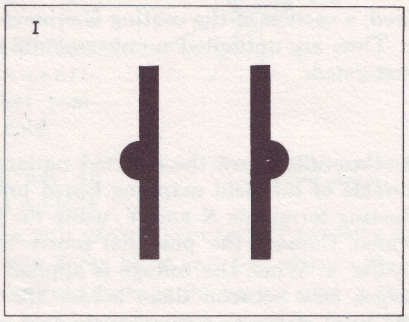
9. What conclusions can you draw about the field strength and the current density at various parts of sheet II, Fig. 7?

10. How much work is done in transferring an electrostatic unit of charge from the one terminal to the other terminal in this experiment?

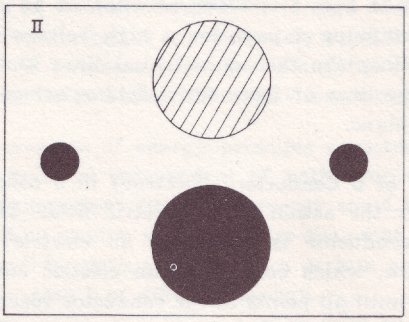
11. Explain the lack of symmetry in the field of sheet I, Fig. 7.

12. Sketch the field pattern of two positively charged small spheres placed a short distance from each other.

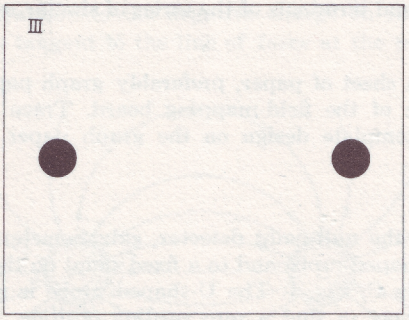
13. Explain the pattern of the field found inside a Faraday "Ice Pail".



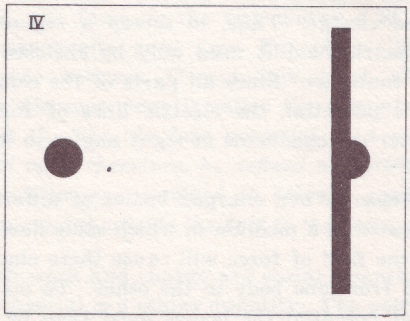
Parallel Plate Capacitor, Cenco No. 079589-002.



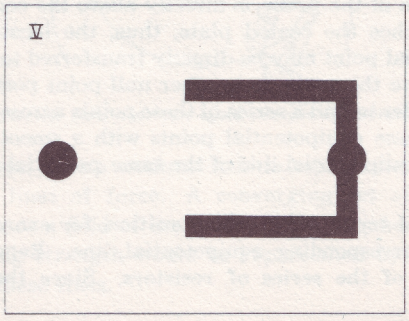
Insulator and conductor in field, Cenco No. 079589-001.



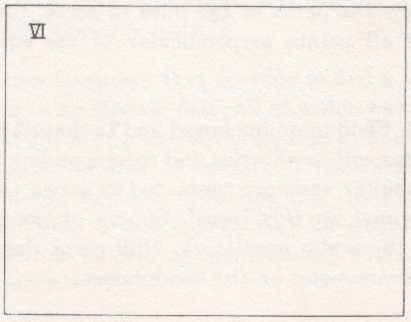
Small circular terminals, Cenco No. 079589-004.



"Point" and Plane, Cenco No. 079589-005.



Faraday "Ice Pail", Cenco No. 079589-003.



Your design, Cenco No. 079589-006.

Fig. 7.

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